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Final Report - Fermi Galactic Transients
BAA 76-13-01: Research into Space, Backgrounds, Imaging and Modeling

Gregory B. Taylor (UNM)

Summary

Multi-wavelength follow-up of γ-ray sources in the galactic plane has been highly successful, resulting in the discovery of a large number of millisecond pulsars, and novae as an entirely new class of γ-ray emitter. Many γ-ray sources in this region are still unidentified, and the probability of new discoveries is high. We were awarded 8 hours of VLA observing time. Several transients were examined but in the end no VLA time was triggered.

Background

The *Fermi*-LAT maps the entire sky every $\sim$3 hrs (two spacecraft orbits) with unprecedented sensitivity and imaging capabilities at $\sim$GeV energies. Since Aug. 2008, the data have been continuously searched for flaring/transient sources via an Automated Science Processing (ASP; Atwood et al. 2009) pipeline that over the first 5+ years of LAT operation, resulted in over 200 public alerts via ATELs on highly significant, $TS > 25$ (i.e., $>5\sigma$) non-GRB GeV sources detected on 1-day timescales. Besides flaring blazars, this surveying capability has led to a new census of bright γ-ray variable Galactic transients including the Crab nebula, X-ray binaries (XRBs), and novae, a newly established GeV source type. With this success in such a short timespan, our expectation is that *even rarer types of Galactic GeV transients will be unveiled as LAT sky surveying continues.* Moreover, the current proposal leverages improved point source sensitivity due to updated LAT calibration (current 'P7REP' instrument response functions), reduced systematics due to Galactic diffuse model, and experience gained over the past cycles in transient identification. This highlights the key role of continued monitoring of LAT data together with prompt multi-wavelength follow-up in identifying and studying new flaring sources in the *Fermi* extended mission.

As part of the *Fermi*-LAT team's multi-frequency efforts aimed at identifying and studying Galactic transients, we obtained an allocation of VLA observing time for follow-up of flaring/transient LAT γ-ray sources near the Galactic plane of up to 2 targets discovered in the period of the 7th and 8th year of *Fermi* operation from Aug. 2014 - July 2016. The VLA observations, the *Swift* XRT and UVOT (U, B, V, $UVW1$ bands) follow-up provide the necessary arcsec-resolution data to search for plausible lower-energy counterparts to the γ-ray transients via the expected correlated variability.

The initial VLA follow-up data we plan to obtain are invaluable to address the nature of each bright *Fermi*-LAT transient regardless of whether a lower energy counterpart can be uniquely attributed to the γ-ray event, or if unexpected flaring is observed in a known source. In the case of the historical April 2011 Crab γ-ray flare, we triggered VLA observations from this program (including further NRAO/DDT time), revealing a variable continuum radio source at the pulsar position, but at no other region within the nebula including the variable X-ray $5.7''$ knot discussed as possibly connected with the γ-ray transient source (Weisskopf et al. 2013). In one intriguing case, Fermi J1057–6027 no plausible counterpart is established.

In summary, following the *Fermi*-LAT detection of a γ-ray source near the Galactic plane ($|b| \lesssim 10°$) flaring with high significance ($\geq 5\sigma$), we had planned to trigger a sequence of four 1 hr VLA observations. The criteria for selection allowed for the source to be either a new γ-ray source, or a known one either previously detected by EGRET or a new LAT source which has brightened to $\geq 3\times$ its mean level. We planned to trigger the VLA observations regardless of its current configuration, since we are *a priori* confronted with an emission phenomenon related to an extremely unusual γ-ray source or even a source class of unknown nature. We also obtained a time allocation with the Long Wavelength Array (LWA) telescope for purposes of obtaining information at radio frequences below 100 MHz.

For the VLA we relied on available dynamic scheduling slots and using short 1 hr slots will increase the probability that the observations will be executed in a timely manner.

The first run sets the stage by identifying all radio sources within the LAT error circle down to a flux limit $\lesssim 0.14$-0.27 mJy (3σ), and can characterize their spatial and spectral properties. This observation must be triggered as quickly as possible (preferably within 24 hrs and certainly within 48 hrs, but we do not require "overrides" of other scheduled observing programs). The rise and decay timescales of the γ-ray transients detected so far have been of order 1–4 days, but since the variability timescale of the radio source is unknown (and will not necessarily match that of the γ-rays), the next three observations should be obtained with separations of 2–4 days to probe radio timescales up to $\sim$2 weeks. Further VLA and VLBA observations may be warranted and these will be considered on a case-by-case basis and requested directly as a DDT proposal to NRAO as was done for the 2011 Crab flare and the 2012 γ-ray novae.

The high γ-ray significance/flux threshold of our ToO trigger means that the LAT sources will be well-localized, although these will depend critically on the local γ-ray background which is variable along the plane, and on the source spectrum. For >0.1 GeV fluxes, $> 0.7 \times 10^{-6}$ ph cm^{-2} s^{-1} ($\Gamma < 2.6$), where Γ is the photon index, LAT will obtain 1σ error circles with radii, $r < 6'$ (compared to $r \sim 0.2^{\circ} - 0.5^{\circ}$ with EGRET).

We had planned to obtain VLA observations in the L-band separated into two 512 MHz bands centered at 1.25 and 1.75 GHz and C-band split into two 1.024 GHz bands centered at 5.0 and 6.0 GHz. The half width at half power of the primary beam of the VLA antennas is $16'$ (ν / 1.4 GHz)$^{-1}$, so the L-band observations require only a single pointing to cover the LAT error circles. Due to the relatively small primary beam at C-band, these observations will require 7 pointings per target in a hexagonal pattern offset by $\sim 3.4'$ for mosaicking (as was done in the case of Fermi J0639+0548 = Nova Mon). In each 1 hr run, we will obtain single 3.5-4 min scans at L-band and at each of the seven C-band pointings, with the remaining time necessary for overhead on calibrators and telescope slew time. The four runs per target should be be separated by 2–4 days thus covering a total of $\sim$ 2 weeks. The total allocation was thus 8 hrs of VLA time for up to 2 such triggers.

As we are observing through the Galaxy, we expect larger rms than the nominal theoretical values. Based on the VLA exposure time calculator, the 1.25 GHz D-array observations will reach the confusion limit of 146 μJy (1σ) after $\sim$ 70s of exposure while the 1.75 GHz observations will approach the confusion limit of 59 μJy in $\sim$ 3.5-4 min. At 5 and 6 GHz, the expected rms $\sim 47\mu$Jy (1σ). The resultant images will be $> 5-10\times$ deeper than existing ones (most importantly, they will coincide with the high-activity state of the γ-ray transient source) and the observing frequencies are chosen to facilitate comparison to historical data obtained at the same frequencies – e.g., the NVSS and the MAGPIS (Helfand et al. 2006) surveys – which can be used to probe the variability of bright point sources on >10 year timescales.

The small LAT error circles will facilitate reliable radio counterpart identifications as we expect only a few random radio sources by chance (whereas, in the case of 3EG sources, there are many 10's to > 100 sources in the error circles; e.g., Tavani et al. 1997, Paredes et al. 2008). Based on 5 GHz observations of the inner Galaxy ($|b| < 0.4^{\circ}$, $l = 350^{\circ} - 40^{\circ}$), Becker et al. (1994) found ten > 2.5 mJy sources deg^{-2}, or 0.08 expected sources within a $r = 3'$ circle. Extrapolating down to lower levels, e.g., 0.25 mJy = 10σ, we expect $50\times$ more sources, or 4 sources by chance in our error circles. Note that source densities drop dramatically away from the inner galaxy and off the plane so these should be considered upper limits. Ultimately, using the VLA monitoring to isolate any variable radio source will provide the necessary arcsec-level positions to help identify optical/infrared counterparts (using DSS/2MASS and newly obtained *Swift*/UVOT images) for further follow-up.

We planned to trigger the VLA observations regardless of its configuration, since we are studying phenomena related to an extremely unusual γ-ray source or even a source class of unknown nature. The VLA will be in its DnC, C, CnB, B, BnA, and A configurations through *Fermi* cycle 7 covering three VLA semesters (2014B, 2015A, B). In the VLA's most extended configurations, the observations will provide additionally arcsec-resolution imaging.

Students supported through this effort

UNM graduate students Ken Obenberger and Karishma Bansal were partially supported by this award. In preparation the students learned how to calibrate and analyze VLA, VLBA and LWA observations. This award also supported the travel of Karishma Bansal to the 2016 AAS meeting in Orlando, Florida where she presented a poster.

References

Becker, W. et al. 1994, ApJS, 91, 347
Hartman, R.C. et al. 1999, ApJS, 123, 79
Helfand, D. et al. 2006, AJ, 131, 2525 (MAGPIS survey)
Nolan, P.L. et al. 2003, ApJ, 597, 61
Nolan, P.L. et al. 2012, ApJS, 199, 31 (2FGL catalog)
Paredes, J.M. et al. 2008, A&A, 482, 247
Roberts, M.S.E., Romani, R.W., Kawai, N. 2001, ApJS, 133, 451
Tavani, M. et al. 1997, ApJ, 479, L109
Weisskopf, M. et al. 2013, ApJ, 765, 56 (2011 Crab flare multi-λ)